

# A degree-day model of *Cirsium arvense* shoot emergence from adventitious root buds in spring

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If decision-aid software models of weed emergence and growth are ever to help producers better time weed management, these models must be able to predict perennial weed shoot emergence from vegetative propagules. In this research, *Cirsium arvense* shoot emergence from adventitious root buds in spring was modeled using degree-day heat sums. Fractional *C. arvense* shoot emergence was best modeled as a logistic dose-response function of degree-day heat sum as follows:  $Y = 1.108 / (1 + [X / 488.344]^{-5.161})$  where  $Y$  = fractional *C. arvense* shoot emergence (0 to 1) and  $X$  = heat sum in degree-days above 0 C after day 91 of the year (April 1) with an upper limit of 800 degree (C) days ( $r^2 = 0.83$ ). This empirical model was validated by graphing observed vs. model-predicted *C. arvense* shoot emergence using two independently gathered data sets, one of *C. arvense* emergence in autumn chisel-plowed *Triticum aestivum* ( $r^2 = 0.82$ ) and the other in no-till fallow ( $r^2 = 0.63$ ). The model slightly overestimated emergence at low fractional emergence (< ~7% at 0.1 fractional emergence) and underestimated emergence at high fractional emergence (10 to 20% at 0.8 to 1.0 fractional emergence). Below an emergence fraction of 0.8, the model adequately estimated observed emergence to within about 10% of the predicted regression line. Using the model, about 1% and 80% of *C. arvense* shoots should emerge from adventitious root buds after a heat sum accumulates of about 197 and 587 C d, respectively, starting from day 91 of the year. Consequently, farmers should begin monitoring *C. arvense* patches for emergence and height growth after about 197 C d accumulate and expect to control *C. arvense* before about 587 C d accumulate, which is when about 80% of shoots have emerged.

**Nomenclature:** *Cirsium arvense* (L.) Scop. CIRAR, Canada thistle; *Triticum aestivum* L., wheat.

**Key words:** Heat sum, temperature, CIRAR.

Weed biology software, such as WeedCast (Forcella 1998), linked with weed control decision-aid software (O'Donovan 1996; Olsen et al. 1996) may help improve the efficacy and profitability of weed management while minimizing unintended negative environmental effects such as soil erosion and water contamination by herbicides, fertilizers, and sediment. Weed biology software may help improve mechanical weed control such as rotary hoeing (Oriade and Forcella 1999) or field cultivation, as well as herbicide application (Fidanza et al. 1996; Forcella and Banken 1996) by better timing and matching weed control measures to when mixed weed populations emerge and are most susceptible to control.

WeedCast software is one way of packaging weed biology information so that producers can best make weed management decisions. But databases of weed emergence phenology and early-season growth are needed if such weed biology decision aids are to become more useful.

WeedCast relies, in part, on heat sum (degree-day) models of annual grass and broadleaf weed emergence and height growth (Forcella 1998). But few degree-day models for perennial weed emergence from buds have been published. Earlier, heat sum models of *Sorghum halepense* (L.) Pers. shoot emergence from rhizome buds showed promise for guiding weed control decisions, such as timing herbicide application (Ghersa et al. 1990; Satorre et al. 1985). However, there is disagreement on the accuracy of an earlier *S.*

*halepense* thermal model developed by Satorre et al. (1985) in different crop environments (Vitta and Leguizamon 1991). To date, models such as WeedCast have not modeled perennial weed emergence from vegetative propagules such as adventitious root buds on overwintering perennial root systems or of shoot buds on rhizomes.

The first objective of this research was to determine whether the primary tillage system (i.e., autumn moldboard-plowing, autumn or spring chisel-plowing, or no-till) before planting *Triticum aestivum* influenced the spring emergence phenology of *C. arvense* shoots from adventitious root buds. The second objective was to determine whether heat sums using air temperature degree-days accumulated after April 1 (day 91 of the year) adequately modeled *C. arvense* shoot emergence. A third objective was to validate the *C. arvense* emergence model against independent data sets gathered at nearby sites in autumn chisel-plowed *T. aestivum* and no-till fallow.

## Materials and Methods

### Experimental Site

All experiments were conducted during 1987 and 1989 on the North Dakota State University main station and NW22 experimental farms in or near Fargo, ND (46° 16.36 N, 96° 14.54 W, 272 m altitude) on a Fargo silty clay (fine, montmorillonitic, frigid Vertic Hapliquoll) with 2.5% sand,

TABLE 1. Dates of field operations and *Cirsium arvense* shoot emergence observation.

Experiment	Treatment or measurement	Trial 1	Heat sums	Trial 2	Heat sums
			after day 91		after day 91
			°C		
			°C		
Primary tillage study in <i>Triticum aestivum</i>	Autumn chisel-plowed	10/15/86	n/a	9/27/88	n/a
	Autumn moldboard-plowed	10/23/86	n/a	9/27/88	n/a
	Spring chisel-plowed	4/20/87	198	4/21/89	75
	Field cultivated-harrowed for seedbed preparation	4/21/87	205	4/28/89	164
	Glyphosate applied to no-till plots	4/24/87	239	4/21/89	75
	<i>T. aestivum</i> planted and fertilized	4/28/87	301	5/1/89	182
	Counted shoots	1 4/22/87	216	5/1/89	182
		2 4/30/87	327	5/8/89	248
		3 5/7/87	434	5/15/89	377
		4 5/15/87	589	5/22/89	499
		5 6/4/87	905	6/1/89	641
		6 n/a	n/a	6/15/89	848
Chisel-plowed study in <i>T. aestivum</i>	<i>T. aestivum</i> starting to emerge	5/7/87	434	5/8/89	248
	Autumn chisel-plowed	10/7/86	n/a	10/10/88	n/a
	Field cultivate-harrow for seedbed preparation	4/17/87	142	4/28/89	164
	<i>T. aestivum</i> planted and fertilized	4/28/87	301	5/1/89	182
	Counted shoots	1 4/10/87	69	4/10/89	11
		2 4/28/87	301	5/1/89	182
		3 5/4/87	384	5/8/89	248
		4 5/7/87	434	5/15/89	377
		5 5/11/87	510	5/26/89	555
		6 5/15/87	589	6/2/89	655
		7 5/20/87	660	6/8/89	745
		8 6/4/87	905	6/15/89	848
No-till study in fallow without <i>T. aestivum</i>	Counted shoots	9 6/11/87	1,037	6/23/89	1,015
		10 6/26/87	1,381	6/30/89	1,162
		11 7/9/87	1,653	7/10/89	1,419
		12 n/a	n/a	7/17/89	1,579
		1 4/20/87	198		
		2 5/05/87	401		
		3 5/15/87	589		
		4 6/02/87	872		
		5 6/15-16/87	1,131		
		6 6/30/87	1,456		
		7 7/14/87	1,742		
		8 7/28/87	2,091		

51.7% silt, 45.8% clay, 4.8% organic matter, and pH 7.9. Well established, dense *C. arvense* ssp. *arvense* (Wimm. and Grab.) was studied (Moore and Frankton 1974).

### Primary Tillage Study in *T. aestivum*

The primary tillage treatments were (a) autumn moldboard-plowing, (b) autumn chisel-plowing, (c) spring chisel-plowing, (d) glyphosate-treated no-till, and (e) unsprayed weedy no-till. The site had been infrequently mowed but not tilled during the two years before initial autumn tillage in 1986. Emerged winter annual broadleaf and grass weeds present on chisel- and moldboard-plowed plots were controlled by field cultivation-harrowing for seedbed preparation. Glyphosate was applied at 840 g ha<sup>-1</sup> plus nonionic surfactant (X-77) at 0.25% (v/v) for winter annual weed control in no-till but before *C. arvense* emergence. The crop was *T. aestivum* cv. Wheaton, a semi-dwarf hard red spring wheat. *T. aestivum* was planted with a no-till double-disc grain drill<sup>1</sup> at 100 and 90 kg ha<sup>-1</sup> 3.8 to 5 cm deep in rows

spaced 17.5 cm apart in 1987 and 1989. In 1987 and 1989, *T. aestivum* density averaged 170 and 110 plants m<sup>-2</sup>, respectively. Maximum *C. arvense* density was 74 and 89 shoots m<sup>-2</sup> in 1987 and 1989, respectively. In both years, *C. arvense* emergence preceded *T. aestivum* emergence. The dates of field operations and measurements are summarized for all studies in Table 1.

### Autumn Chisel-Plowed Model Validation Data Set

Shoot emergence was determined over time across a well-established *C. arvense* patch planted to *T. aestivum* for previous experiments (Donald 1994b; Donald and Khan 1992). The site had been mowed in 1986 and was chisel-plowed in the autumn of 1986 and 1988. Emerged annual broadleaf and grass weeds present before planting were controlled by field cultivation-harrowing for seedbed preparation. *T. aestivum* was sown as described above. Maximum *C. arvense* shoot density was 45 and 98 shoots m<sup>-2</sup> in 1987 and 1989, respectively.

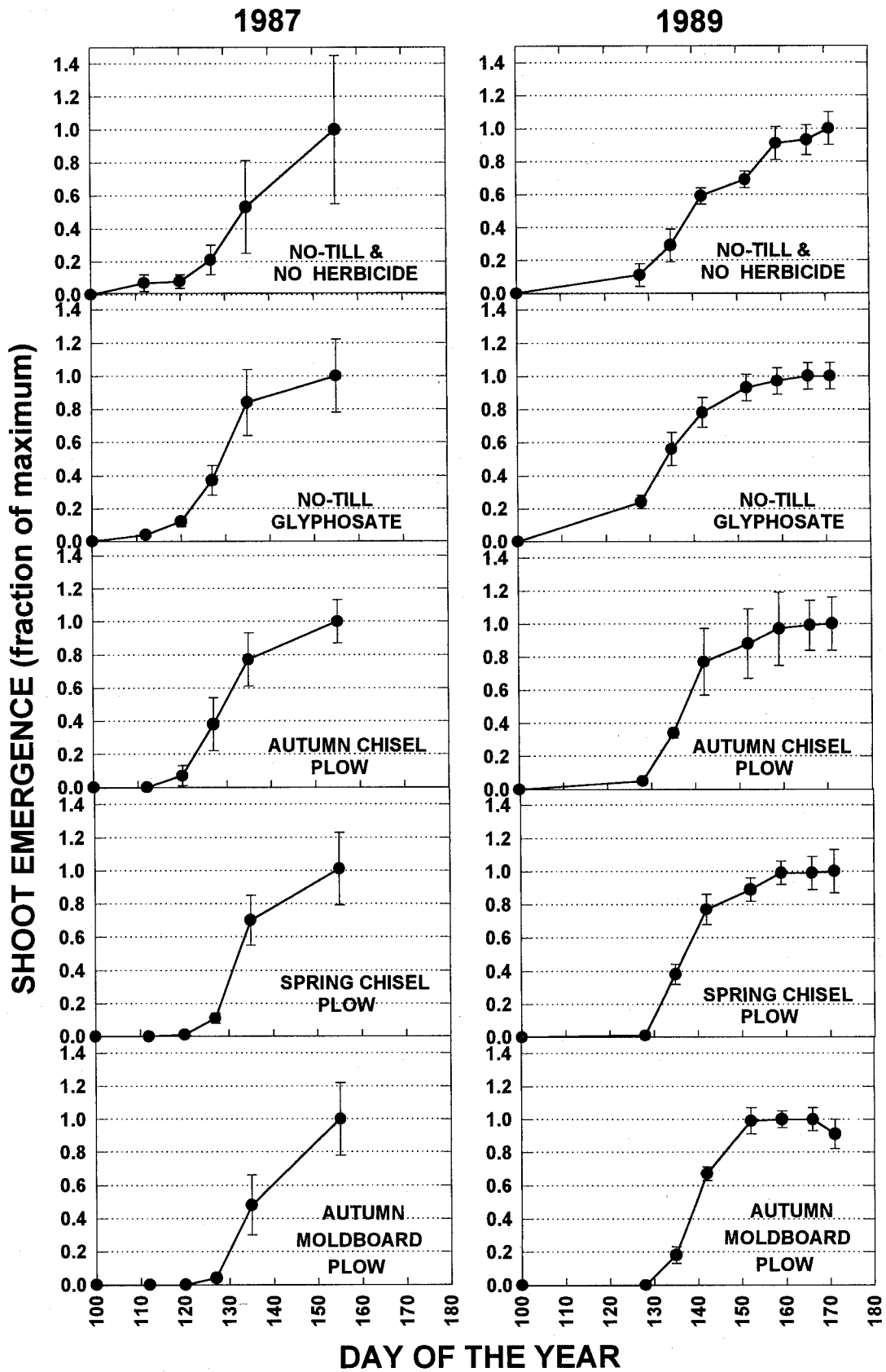


FIGURE 1. The effect of primary tillage system on shoot emergence from adventitious root buds of well-established *Cirsium arvense* in *Triticum aestivum* in spring near Fargo, ND, in 1987 and 1989. Shoot counts are presented as a fraction of the maximum average per growing season. Means  $\pm$  standard errors are presented.

TABLE 2. Statistical significance of orthogonal contrasts for *Cirsium arvense* shoot emergence between various primary tillage treatments at various days of the year.

Orthogonal contrast	Day of Year						
	1987		1989				
	112	120	128	135	142	152	159
No-till vs. tilled (moldboard + chisel-plowing)	0.037	ns	0.001	0.063	ns	ns	ns
Autumn vs. spring chisel-plowing	ns	ns	ns	ns	ns	ns	ns
Autumn moldboard-plowed vs. (autumn + spring chisel-plowing)	ns	ns	ns	ns	ns	ns	ns
No-till, no herbicide vs. no-till, glyphosate	ns	ns	0.013	0.018	0.048	0.030	ns

### No-Till Fallow Model Validation Data Set

*C. arvense* shoot emergence was observed over time in untreated check plots in no-till fallow for Trials 2 and 3 in 1987 for a previously published study (Donald 1993). Maximum *C. arvense* shoot density was 39 shoots m<sup>-2</sup> in 1987.

### Measurements

Emerged *C. arvense* shoots arising from adventitious root buds were counted in randomly placed quadrats. In the primary tillage study, eight circular quadrats (each 0.2 m<sup>2</sup>) were placed in each plot shortly after *T. aestivum* planting but before *C. arvense* shoot emergence (Table 1). In the chisel-plowed study, 47 and 60 square quadrats (each 0.75 m<sup>2</sup>) were placed in 1987 and 1989, respectively, shortly after *T. aestivum* was planted but before *C. arvense* shoots emerged (Table 1). In the fallowed no-till study, three circular quadrats (0.2 m<sup>2</sup>) were placed per plot (Table 1).

Climate data (maximum and minimum air temperature and precipitation) were obtained from the National Oceanic and Atmospheric Administration (NOAA) weather station at Fargo International Airport, which is located between the NW22 and main experimental farms.

### Experimental Design and Statistical Analysis

A randomized complete block design with three blocks was used for the *T. aestivum* primary tillage study and the no-till fallow study. Blocking was based on *C. arvense* shoot density observed one year earlier. Plots measured 3 m by 24 m in the primary tillage study and 1.8 m by 7.6 m in the no-till fallow study. A completely randomized design was used in the chisel-plowed *T. aestivum* study.

*C. arvense* shoot density was expressed per unit area averaged over the number of quadrats per plot in the primary tillage and the no-till fallow studies. Because average *C. arvense* shoot density differed between blocks, years, treatments, and sites, emergence density data were normalized by expressing density as a fraction of the average maximum seasonal emergence per treatment. The date when maximum seasonal emergence was observed differed between years and was not related to later degree-day modeling. Calendar dates were converted to day of the year.

In the primary tillage study, fractional (normalized) emergence was subjected to ANOVA<sup>2</sup> to examine the effect of year, primary tillage treatment, and ranked day of the year on shoot emergence. Specific treatment means or grouped means were compared using orthogonal contrasts for each day of the year in which observations were made. Treatment

means also were separated using Fisher's Protected LSD test at  $P < 0.05$  for each day separately each year.

Heat sums (temperature units or cumulative growing degree days [GDD]) were calculated starting after April 1 (day 91 of the year) above a base temperature ( $T_{\text{base}}$ ) of 0 C as defined in Method 1 of McMaster and Wilhelm (1997) below:

$$\text{GDD} = ((T_{\text{max}} + T_{\text{min}})/2) - T_{\text{base}}$$

where if  $((T_{\text{max}} - T_{\text{min}})/2) < T_{\text{base}}$ , then  $((T_{\text{max}} - T_{\text{min}})/2) = T_{\text{base}}$

$$\text{HS} = \sum_{i=1}^n \text{GDD}$$

until HS = 800 C, where HS is the heat sum or cumulative GDD (C), GDD is the growing degree day,  $T_{\text{max}}$  is the maximum daily temperature,  $T_{\text{min}}$  is the minimum daily temperature,  $T_{\text{base}}$  is the base temperature, and  $n$  is the number of days elapsed since day 91 (April 1). Emergence of winter-hardy *T. aestivum* also is calculated using a base temperature of 0 C (McMaster and Smika 1988). Of course, other base temperatures may be more appropriate for modeling later growth stages of *C. arvense*.

Fractional *C. arvense* emergence was expressed as a function of heat sums using linear and nonlinear least squares regression (Kleinbaum and Kupper 1978; Neter et al. 1989; Seefeldt et al. 1995) performed by TableCurve 2D curve-fitting software.<sup>3</sup> Because maximum emergence was completed by a minimum heat sum of about 800 degree-days, data for heat sums greater than this were excluded from analysis. The adequacy of candidate regression equations was determined by examining  $r^2$  statistics, lack-of-fit error, and inspection of plots of residuals vs. the independent variable of the regression equations. Regression coefficients were significantly different from zero, and over-specified linear and nonlinear regression models with coefficients that were non-significant were eliminated from consideration. Nonlinear regression models were compared using the "lack-of-fit" or "goodness-of-fit" F-test (Neter et al 1989; Seefeldt et al. 1995) after grouping data as either no-till and tilled (autumn moldboard-plow + autumn chisel-plow + spring chisel-plow) from the primary tillage experiment.

The nonlinear regression model chosen for further study (logistic dose-response of fractional emergence vs. heat sum) was tested against two independently gathered *C. arvense* emergence data sets (i.e., chisel-plowed *T. aestivum* in 1987 and 1989 and no-till fallow in 1987, described above). Observed fractional emergence for these data sets was regressed

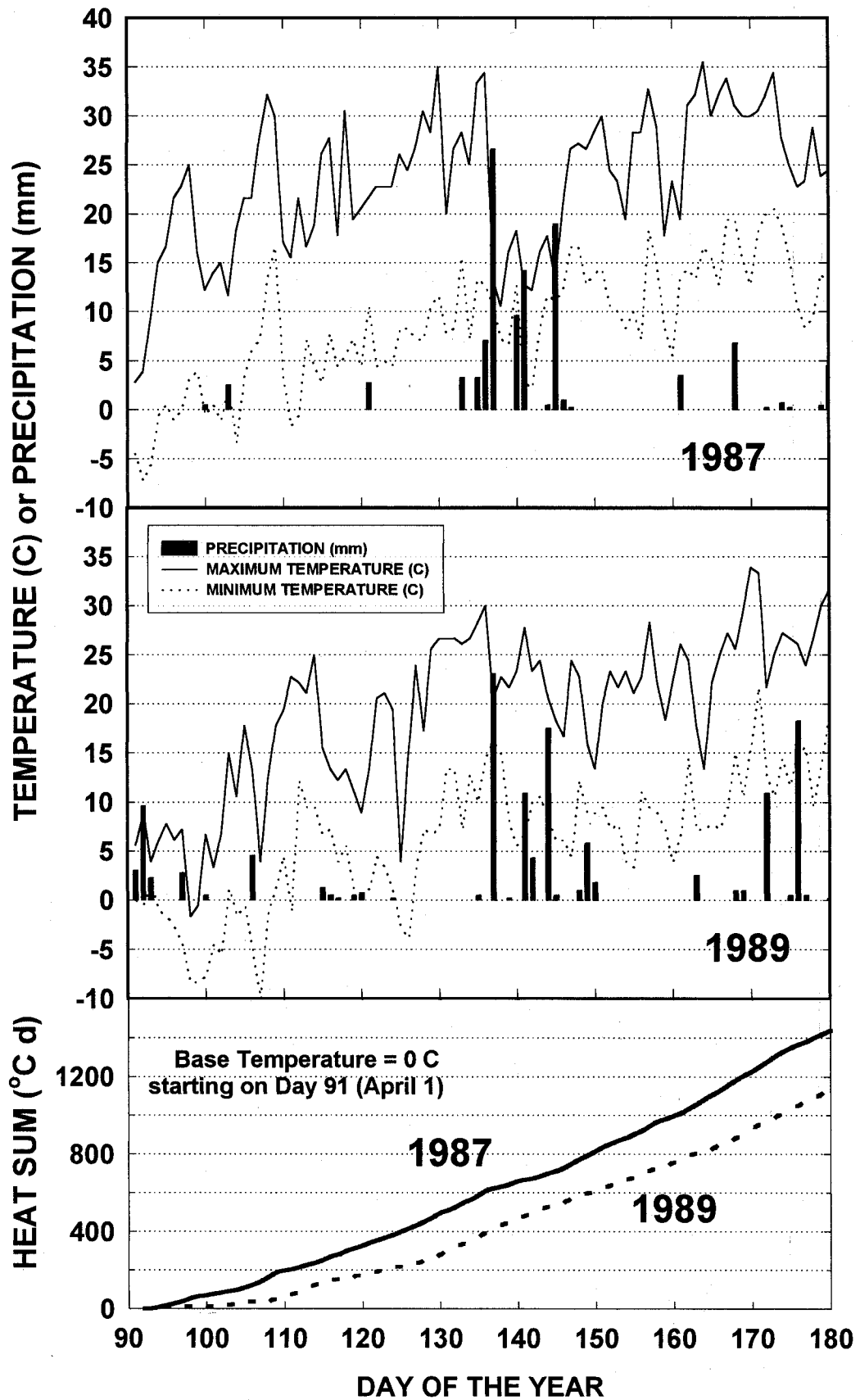


FIGURE 2. Maximum and minimum daily air temperature, daily precipitation, and heat sums in cumulative degree-days above a base temperature of 0 C starting on day 91 of the year (April 1) graphed vs. day of 1987 and 1989 near Fargo, ND.

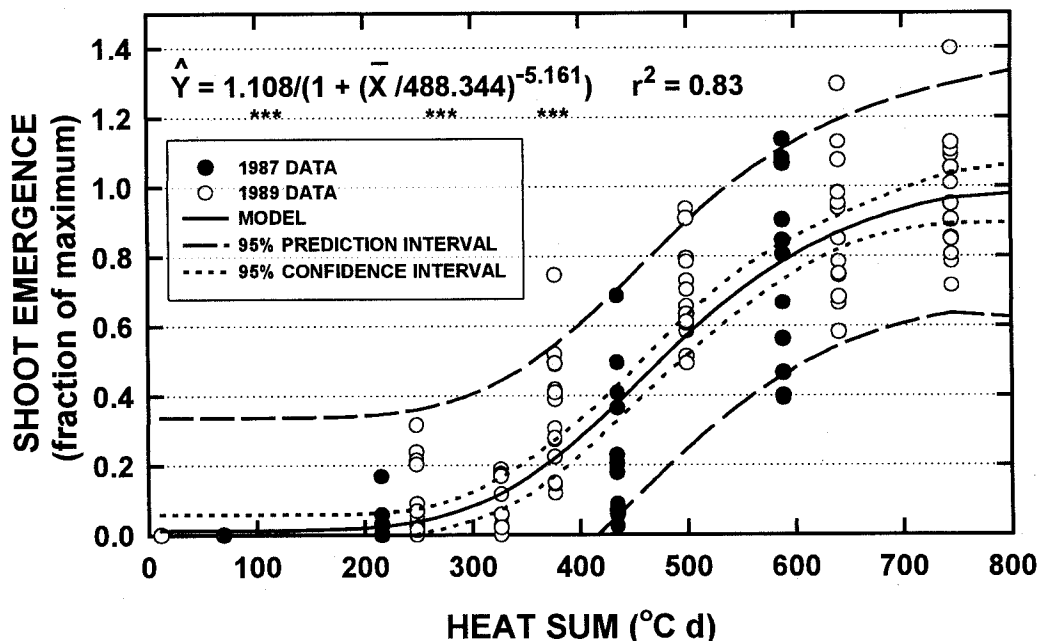


FIGURE 3. A nonlinear logistic dose-response regression model of *Cirsium arvense* shoot emergence from adventitious root buds in spring vs. heat sums in cumulative degree-days above a base temperature of 0 C starting day 91 of the year (April 1). Data from both years of the primary tillage study in *Triticum aestivum* for heat sums less than 800 degree-days were combined for regression analysis.

on predicted emergence using a logistic dose-response model.

## Results and Discussion

### Primary Tillage Study

Because there were significant year by treatment and year by ranked date interactions (data not presented), results are expressed separately by year, treatment, and day of the year (Figure 1).

Reportedly, no-till encourages perennial weed encroachment over time (Buhler et al. 1994; Derksen et al. 1995, 1996; Frick and Thomas 1992; Triplett and Lytle 1972). *C. arvense* shoot emergence from adventitious root buds can be denser and earlier in no-till than following tillage (Figure 1), even though no-till soil surfaces generally warm more slowly than do tilled surfaces. When perennial roots of *C. arvense* are left undisturbed in fall and winter, underground adventitious root buds grow toward the soil surface over winter (Donald 1994a; McAllister and Haderlie 1985; Rogers 1929). Although it has not been measured, these field observations suggest that *C. arvense* adventitious root bud growth may have a lower temperature threshold than does annual weed seed germination. Tillage fragments *C. arvense* roots and buries root buds more deeply than normal. Root burial and fragmentation may limit and delay subsequent adventitious root bud growth toward the soil surface because smaller root fragments have less nutrient and energy storage reserves than larger undisturbed root systems in spring. Moldboard-plowing was expected to delay shoot emergence compared with chisel-plowing because moldboard-plowing inverts and buries soil and root fragments more deeply than does chisel-plowing. However, by maximum emergence each year (day 155 of 1987 and day 171 of 1989), differences in emergence could not be distinguished among treatments expressed as either absolute (data not presented) or fractional

*C. arvense* shoot density (Table 2 and Figure 1). When averaged across treatments, shoot density was 41 ( $\pm 4$ ) m<sup>-2</sup> (mean  $\pm$  stand error) on day 155 of 1987 and 70 ( $\pm 3$ ) m<sup>-2</sup> on day 171 of 1989.

Although tillage did not influence shoot density by the end of observation each year, orthogonal contrasts for each day of each year uncovered differences in shoot emergence among treatments when emergence was first observed (day 112 of 1987 and day 128 of 1989) (Table 2). Orthogonal contrasts showed that in both years *C. arvense* emerged earlier in no-till (with or without preemergence glyphosate) than in tilled treatments (i.e., autumn moldboard-plowed + autumn chisel-plowed + spring chisel-plowed) (Table 2 and Figure 1). In both years, shoot emergence was no different between autumn or spring chisel-plowed treatments at any observation time. Likewise, shoot emergence in both years was no different between the autumn moldboard-plowed plus two chisel-plowed treatments together. In 1987, the no-till treatment with preemergence glyphosate could not be distinguished from the unsprayed no-till treatment at any observation day. But in 1989, more shoots emerged earlier in the glyphosate-treated no-till plots than in unsprayed no-till plots, for unknown reasons (Table 2 and Figure 1).

*C. arvense* shoots emerged earlier in 1987 than in 1989 in all treatments, but most obviously in the autumn moldboard-plowed and spring chisel-plowed treatments (Figure 1). Rainfall patterns were similar both years, but maximum and minimum temperatures were higher earlier in 1987 than in 1989 (Figure 2). Likewise, the heat sum in cumulative degree-days above a base temperature of 0 C starting day 91 of the year (April 1) was higher earlier in 1987 than in 1989.

### Degree-Day Heat Sum Model of *C. arvense* Shoot Emergence

Fractional shoot emergence from adventitious root buds was expressed as a function of heat sums using air temper-

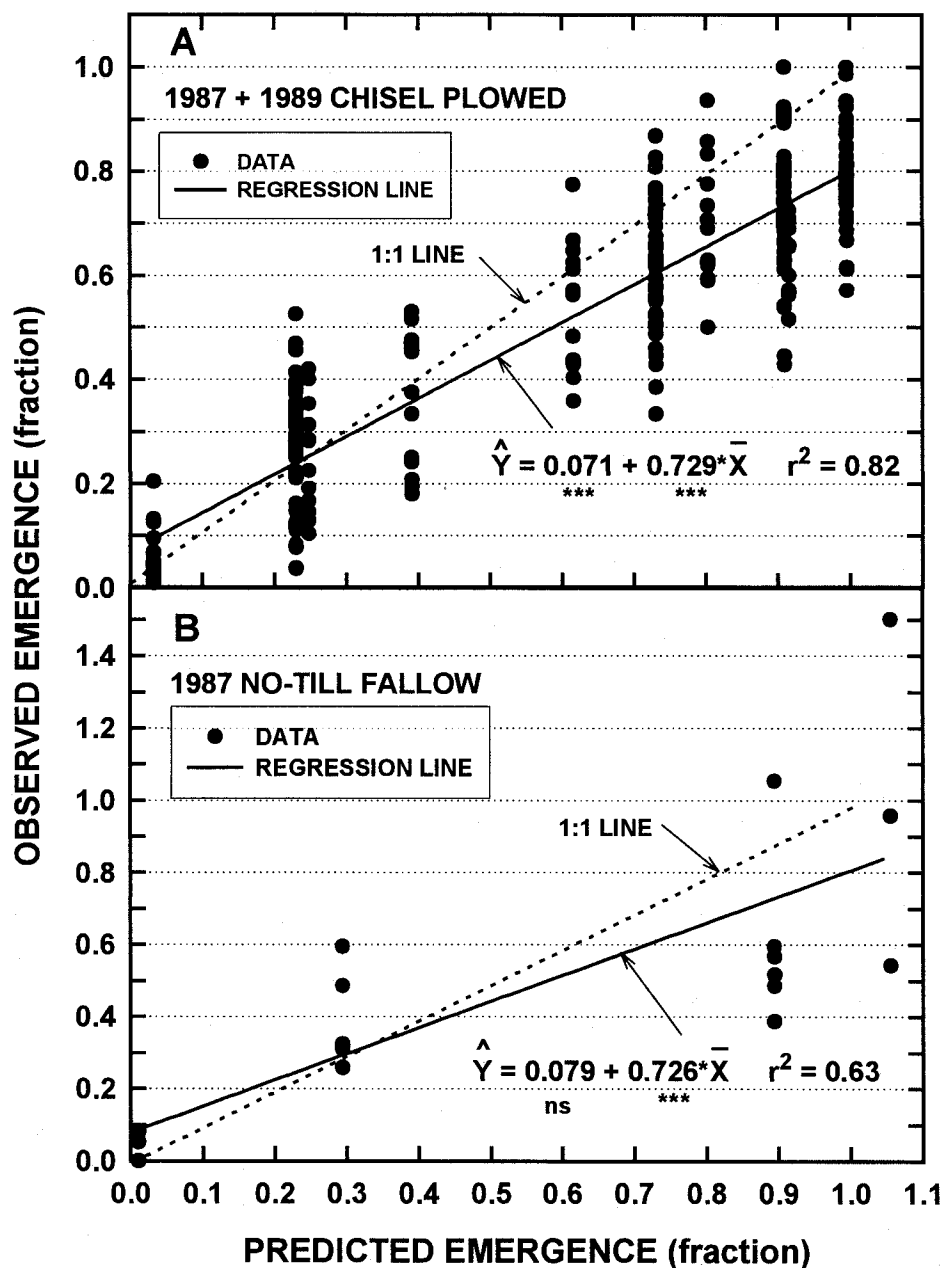


FIGURE 4. Observed *Cirsium arvense* shoot emergence vs. emergence predicted from the nonlinear logistic dose–response regression of Figure 3. An independent data set was used for *C. arvense* emerging in spring in *Triticum aestivum* in 1987 and 1989 following autumn chisel-plowing in the previous years (A) and in no-till fallow in 1987 (B).

ature (i.e., cumulative degree-days above a base temperature of 0 C starting on day 91 of the year) (Figures 2 and 3). Air temperature was used for heat sum calculations rather than soil temperature because air temperatures are routinely measured by NOAA weather stations. In contrast, soil temperature data are not routinely gathered and are more limited in scope. Soil temperature data were not available for this study. A base temperature of 0 C was chosen because adventitious root buds of *C. arvense* reportedly grow toward the soil surface in autumn after shoot death and over winter, although subzero temperatures limit overwinter growth (McAllister and Haderlie 1985; Rogers 1929). Base temperature can also be calculated from field observations (Snyder et al. 1999). In this method, the regression of fractional emergence on heat sums is re-evaluated using heat sums

with base temperatures ranging between 0 and 10 C in 1-degree increments. A nonlinear (logistic dose–response) regression model with a base temperature of 0 C was chosen because the residual mean square error was lowest and the  $r^2$  was greatest compared with other models tested with different base temperatures (Snyder et al. 1999). Alternative linear models of fractional shoot emergence vs. heat sums fitted the data poorly and always explained a smaller portion of data variability than nonlinear logistic dose–response models.

Although the choice of nonlinear model is entirely empirical, a logistic dose–response function was selected to express fractional emergence as a function of heat sums because it fitted the data well, based on criteria of simplicity, a minimal residual sums of squares, nonsignificant lack-of-

fit error, a high  $r^2$ , and examination of residual plots. The logistic dose-response function did not overfit the data because its three coefficients were each significantly different from zero.

Nonlinear regression relationships were also calculated separately for no-till and tilled treatments averaged across years. But when the tilled and no-till logistic dose-response models were compared using goodness-of-fit F tests, the models could not be distinguished from one another. Consequently, the logistic dose-response function relating fractional emergence to heat sums was recalculated combining data for all tillage treatments both years (Figure 3).

The logistic dose-response model was tested using two data sets that were independently gathered at nearby sites. In these data sets, spring *C. arvense* shoot emergence was followed in autumn chisel-plowed *T. aestivum* (Figure 4A) and no-till fallow (Figure 4B). Even though air temperature data from the same weather station in the same years were used for heat sum calculation, emergence data at these additional sites were gathered on different days than for the primary tillage study. Consequently, heat sums differed slightly between data sets. Observed shoot emergence in autumn chisel-plowed *T. aestivum* (Figure 4A) and no-till fallow (Figure 4B) was linearly related to predicted shoot emergence based on the logistic dose-response model (Figure 3). In both cases, the model best estimated shoot emergence below a fractional shoot emergence of 0.6, but it slightly overestimated emergence (~7 %) at low density below a fractional emergence of 0.1. Above a fractional density of 0.8, the model underestimated emergence between about 10 and 20% and was least accurate at 100% emergence. Increased error at the extreme lower and upper tails of the logistic dose-response shoot emergence model was expected because of the function's nonlinearity. Coefficients of determination for the regression of observed vs. predicted fractional shoot emergence were greater for the autumn chisel-plowed *T. aestivum* data set ( $r^2 = 0.82$ ) than for the no-till fallow data set ( $r^2 = 0.63$ ), probably because of its sample size.

This research demonstrates that the simple nonlinear model equation in Figure 3 adequately estimates *C. arvense* shoot emergence from adventitious root buds using heat sums based on air temperature starting on day 91 of the year even though shoots emerge slightly earlier in no-till than in either moldboard- or chisel-plowed tillage systems (Figure 1). Current and historic air temperature data are widely available in the United States from NOAA weather stations. Because it is a constant, day of the year should be used as a starting point for accumulating heat sums rather than accumulating heat sums after field operations such as planting. Using the equation of Figure 3, about 1% of *C. arvense* shoots should emerge from adventitious root buds after a heat sum accumulation of about 197 C d starting from day 91 of the year. Likewise, between 80% and 90% of *C. arvense* shoots should have emerged after about 587 and 648 C d accumulate. Consequently, farmers should begin monitoring *C. arvense* patches for emergence and height growth after about 197 C d accumulate. They should expect to need to control *C. arvense* before about 587 C d accumulate, which is when about 80% of shoots have emerged.

## Sources of Materials

<sup>1</sup> Double-disc grain drill with deep-banding fertilizer attachment, Haybuster 107, Haybuster Manufacturing, Box 1950, Jamestown, ND 58401.

<sup>2</sup> ANOVA Regression Models 9.0 and Advanced Models 9.0, SPSS, Inc., 233 South Wacker Dr., 11th Floor, Chicago, IL 60606-6307.

<sup>3</sup> Curve-fitting software, TableCurve 2D v. 4.0, Jandel Scientific Software, Inc., 2591 Kerner Blvd., San Rafael, CA 94901.

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